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X-RAY INVESTIGATION AND STRENGTH MEASUREMENT OF STEEL FIBRE REINFORCED SELF-COMPACTING CONCRETE BEAMS

Abstract

The paper presents a study on self-compacting concrete with two types of steel fibres. Under consideration was the effect the method of forming of beam elements has on the distribution of steel fibres. Formed we beams of dimensions 120×15×15 cm^3 and 180×15×15 cm^3. The self-compacting mixture contained steel fibres of varying lengths (35 and 50 mm) and varying levels of their volume ratio in the mix (0.5% - 1.0% - 1.5%).

Keywords

Steel fibre, self-compacting concrete, fibre orientation, X-ray Computed Tomography.

1 INTRODUCTION

One of the little researched areas is the effect of forming methods of steel fibre reinforced self-compacting concrete (SFRSCC) on maintaining the assumed design parameters of technological and mechanical properties of concrete. There is no information on the actual dispersion and orientation of fibres in the mixture in the course of technological processes. Investigation of the effect of steel fibres on the self-compactibility of concrete are known [1] [2] [3], including examination of the mechanical properties of SFRSCC [4] [5] [6]. However, studies on the development of this technology, including the deployment of fibre in the mixture are far less advanced. This is due to the complexity of such advanced research methods and limited mean fibre for verifying such concrete structures. The addition of dispersed reinforcement enhances to varied degree the SFRSCC parameters, but at the same time creates difficulties in preparing a composition which satisfies the conditions of a self-compacting, homogeneous matrix in the whole volume, and also significantly improves the physic-mechanical properties [7] [8]. The essence of the problem is to determine what changes in fibre deployment occur in various structural elements when the method of their forming changes, taking into account the rheological properties of the mixture, as well as the volume ratio and the geometrical parameters of steel fibres. The main objective of this study was to determine the distribution and orientation of steel fibres in the tested SFRSCC for a chosen structural model.

2 ASSUMPTIONS AND METHODOLOGY OF RESEARCH

As structural models, there were chosen concrete beams with dimensions 120×15×15 cm^3 or 180×15×15 cm^{3}formed from one edge point (see, in Fig. 1), and after hardening they were cut into two or three samples with dimensions 60×15×15 cm^3.

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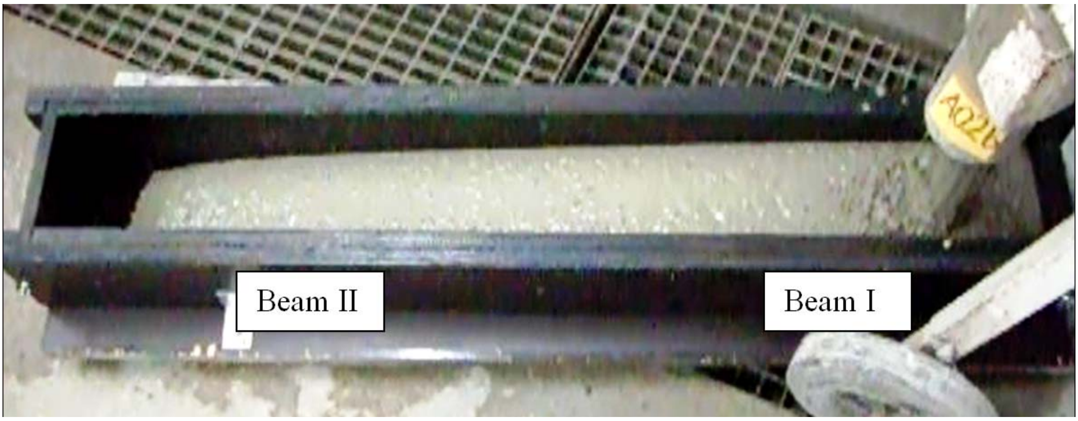


Fig. 1: Forming concrete beams 120×15×15 cm^3, subjected to further testing as two separate beams

These beams were analyzed by computed tomography, as described in more detail in [9] and also were subject to tensile tests in bending, according to RILEM recommendations [10]. The composition of the self-compacting mixtures is presented in Table 1. Two types of steel fibres were considered on three levels of volume ratio. Geometric and material characteristics of steel fibres studied are presented in Table 2. The self-compactibility of the mixture met the criterion throughout the interval of varying fibre content. The reference sample mix of self-compacting concrete was characterized by the flow diameter SF = 770 mm. Adding SW35 and SW50 fibres did not decrease significantly the value of SF, thanks to good plastic viscosity of the reference sample SCC mix.

Tab. 1: Self-compacting mixes containing steel fibres

Component	**kg/m^3**
CEM I	490.0
Sand 0-2 mm	800.0
Crushed pebbles 2-8 mm	800.0
Steal fibres (0.5 - 1.0 - 1.5%)	40-80-120
Superplasticizer Glenium SKY 592 (3.5 % m.c.)	17.2
Stabilizer RheoMATRIX (0.4 % m.c.)	1.96
Sand point (%)	50.0
W/C ratio	0.41
Class of concrete consistency (SF) = 770 mm	SF3

Tab. 2: The geometric and material characteristics of steel fibres

Description	**Length (mm)**	**Width (mm)**	**The cross-section**	**Shape**	**Material**	**Tensile strength (N/mm^2)**
SW 35/1.0	35±10%	2.30 - 2.95	part of the circle		Low carbon steel.	880±15%
SW 50/1.0	50±10%	2.30 - 2.95	part of the circle		Low carbon steel.	880±15%

The scope of the study included:

- preparing SCC mixtures for a given composition, Table 1
- adding steel fibres SW35 and SW50 with characteristics shown in Table 2
- checking the consistency class, 10 minutes of after the mixing process ended
- forming of beams with dimensions 120×15×15 cm^3or 180×15×15 cm^3
- removing the beams from forms, 24 hours after forming
- cutting beams into two or three samples of dimensions 60×15×15 cm^3, marking their position as beam I (closest to point of formation), and beam II or III further from the point of formation
- computed tomographic analysis, 7-14 days after forming
- testing for tensile strength in bending (ffl ??), 28 days after forming.

The CT scanner used for testing was equipped with 64 rows of detectors, and the thickness of a native series of CT scan was 0.625 mm, which was the width of a single detector [9]. Samples were being X-rayed (Roentgen radiation was applied). For each concrete beam results included native series saved in DICOM format consisting of a minimum of 950 images, and reconstructed series consisting of a minimum of 1500, taking into account the interval of 50 to 80% of the thickness of the native. Terms of the acquisition were determined by the voltage for the lamp -- not less than 140 kV and by current of 400 mAs. For the purpose of the presented research results, a total 36 000 X-ray images with dimensions 15×15 cm^2each were carried out, using the method of computed tomography, but exclusively for the 120×15×15 cm^3m beams.

3 THE RESULTS AND DISCUSSION

The results of tests for beams formed in a single process but at different distances from the point of formation (Fig. 1). The obtained results showed the effect of the distance from the point of formation of SFRSCC on the distribution of fibres and mechanical parameters. The beam 60×15×15 cm^3cut from 120×15×15 cm^3beam positioned closer to the point of formation is labeled as beam I, and the beam formed respectively further is labeled as beam II. The beams 60×15×15 cm^3cut from 180×15×15 cm^3 cm beam positioned respectively are labeled as beam I, beam II and beam III (farthest from the point of formation). The 2D and 3D images of real distribution of steel fibres in the tested self-compacting concrete beams were obtained by the use of computed tomography method. Fig. 2 shows a selection of 2D and 3D images of steel fibres in the test of SCC with variable content of SW35 fibres. The 3D images are presented in the following order: first from the left – bottom of beam, on the right side - top of beam. The 2D selected images are referring to places of incision created for the testing of tensile strength in bending, according to RILEM recommendations [10].

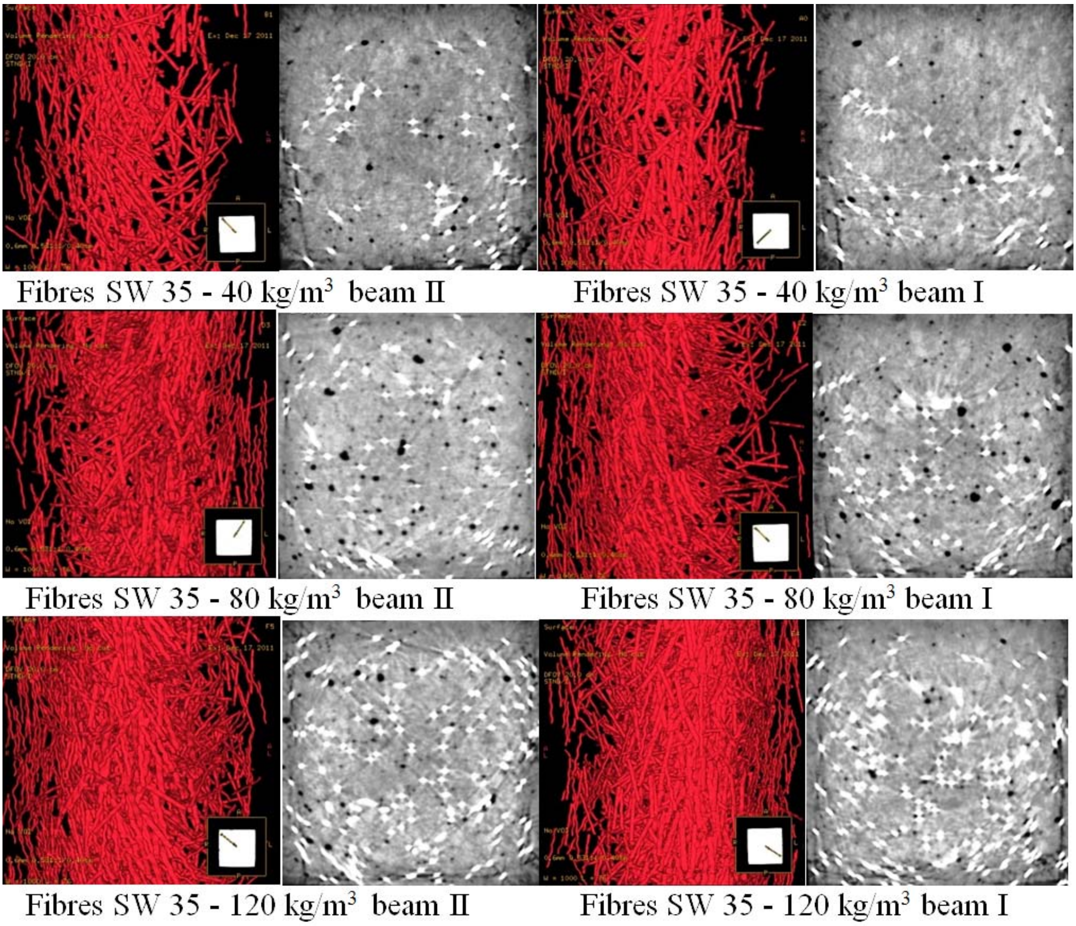


Fig. 2: 2D and 3D view of steel fibres in the tested SCC with variable SW35 fibres content (3D: left – beam's bottom, right – beam top)

For the formed concrete elements, the effect of SW35 fibres content on the tensile strength in bending is illustrated in Fig. 3 (first measurement) and Fig. 4 (second measurement). It has been shown that an increase in strength occurs with increasing content of SW35 fibres in SCC, which was to be expected. On the graphs there were no significant differences in the bending force as a function of beam deflection noticed between beam I and II for SCC with steel fibres SW35. The SFRSCC mixtures and concrete with SW35 fibres are characterized by similar fibre orientation, their arrangement, and similar mechanical properties, regardless of the distance from the point of forming the SFRSCC. There is also similar, uneven distribution of fibres in the cross-sections of all beams (Fig. 2). SW35 fibres are more numerous near the bottom of beams. Noticeable also is the orientation of fibres parallel to the direction of flow of the mixture at formation of SFRSCC. In addition, one can observe an increase in the number of air macro-pores with increasing content of the fibres in the mixture. It is possible to verify the hypothesis of fibres blocking the venting process in SFRSCC mix, especially in places with greater density of fibres in the concrete matrix.

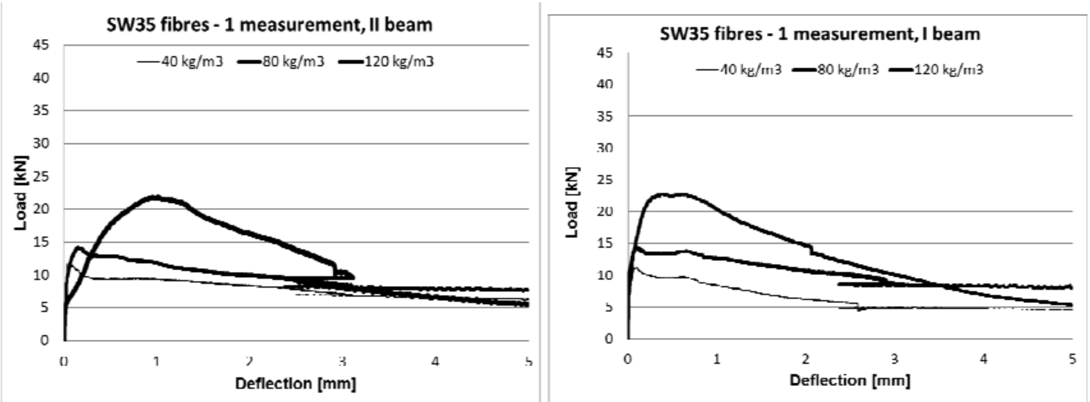


Fig. 3: Effect of steel fibres SW35 on the tensile strength in bending of beam I and beam II in the first measurement.

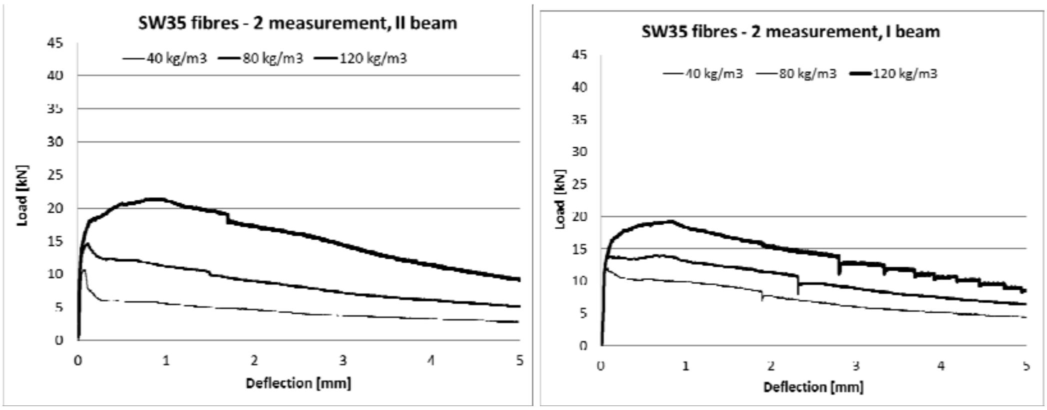


Fig. 4: Effect of steel fibres SW35 on the tensile strength in bending of beam I and beam II in the second measurement.

Fig. 5 shows a selection of 2D and 3D images of steel fibres in the tested SFRSCC with variable SW50 fibre content. Based on X-ray images the same observations were made as to uneven distribution of the fibres, an increase of the amount of fibres in towards the bottom of the beams, orientation of fibres parallel to the direction of flow of the mixture at forming of SFRSCC and an increase of macro-pores with the increase of fibre content in the mixture. For the formed concrete elements, cut from beams 120×15×15 cm^3, the effect of SW50 fibres content on the tensile strength in bending is illustrated in Fig. 6 and Fig. 7. It has been shown that an increase in bending force occurs with increasing content of SW50 fibres in SCC. Additionally, there was greater increase in the bending force for beams II than for beams I with increasing volume ratio of fibres in the test of SCC with SW50. For the content of 120 kg/m^3 the bending force in the beam II (farther from forming point) was greater by 80% than the bending force in the beam I (closer to the forming point). For the SW50 fibre content of 40 kg/m^3 in SFRSCC there was no difference between the forces of bending in the beam I and II. In case of the fibre content of 80 kg/m^3 SW50 WSBSZ has shown an increase in the bending force for the beam II by 35% greater than for the beam I The repeated tests on newly formed beams confirmed these trends.

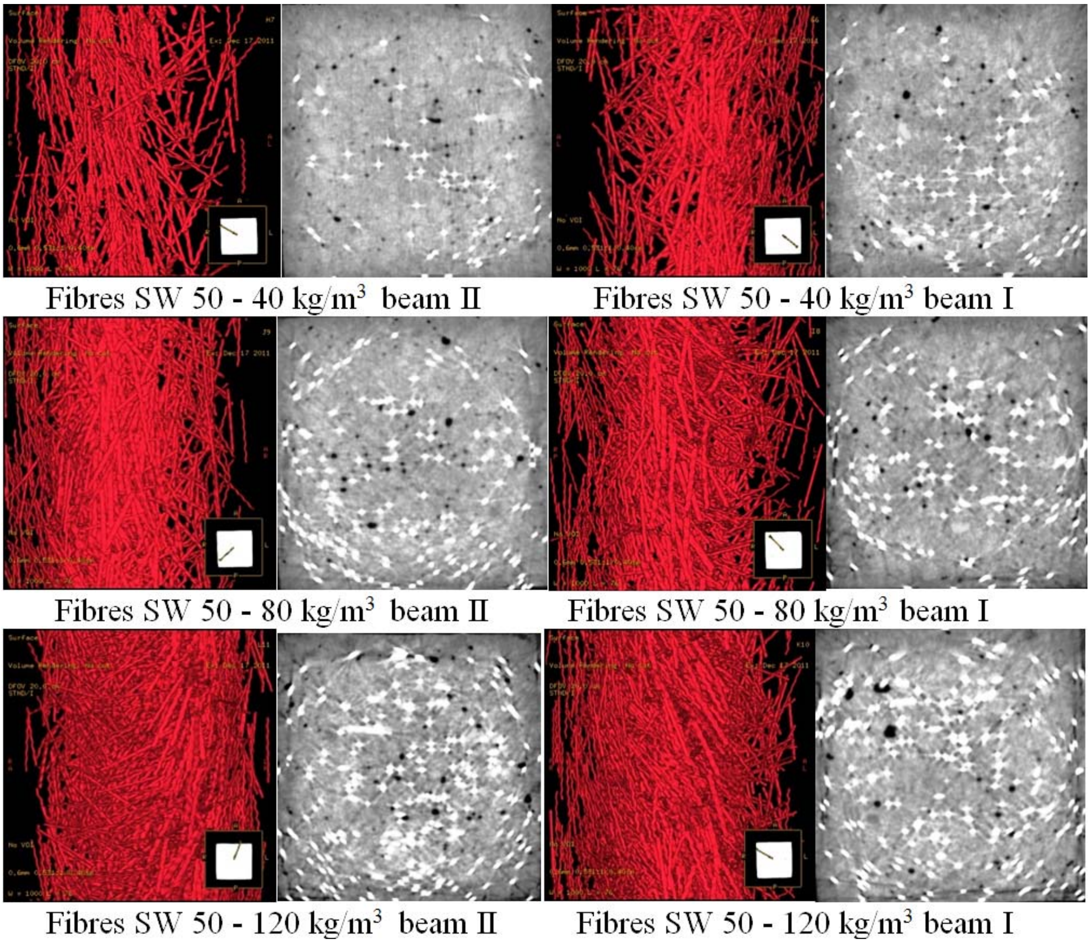
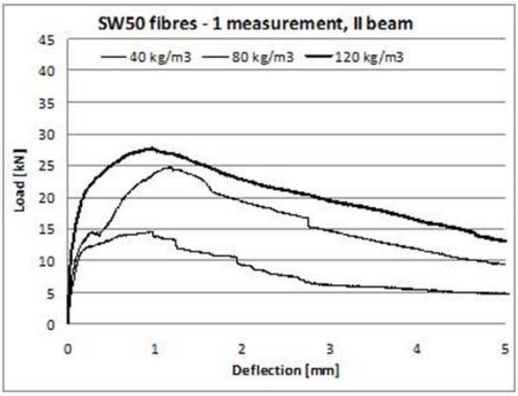


Fig. 5: 2D and 3D view of steel fibres in the tested SCC with variable SW50 fibres content (3D: left – beam's bottom, right – beam's top)

For the formed elements cut from beams 180×15×15 cm^3, the effect of SW50 fibres content on the tensile strength in bending is illustrated in Fig. 8 (left - at formation and the first measurement, right – at forming and the second measurement). It has been shown that an increase in bending force also in these tests occurs with increasing content of SW50 fibres in SCC. Additionally, there was greater increase in the bending force for beam III than for beams I and II with increasing volume ratio of fibres in the test of SCC with SF50. For the SW50 fibres content of 120 kg/m^3 the bending strength in the beam III (farthest from forming point) was greater by 65% than the bending force in the beam I (closest to the forming point). For the SW50 fibre content of 80 kg/m^3 in SFRSCC there was no difference between the bending strength in the beam I, II and III. The repeated tests on newly formed beams confirmed these trends.



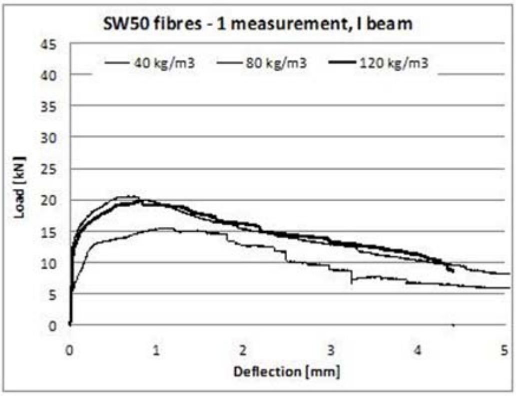
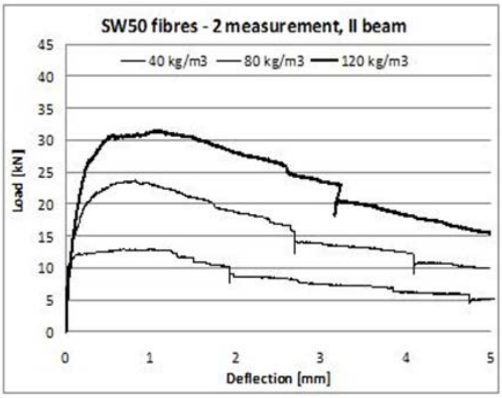


Fig. 6: Effect of steel fibres SW50 on the tensile strength in bending of beams I and II in the first measurement



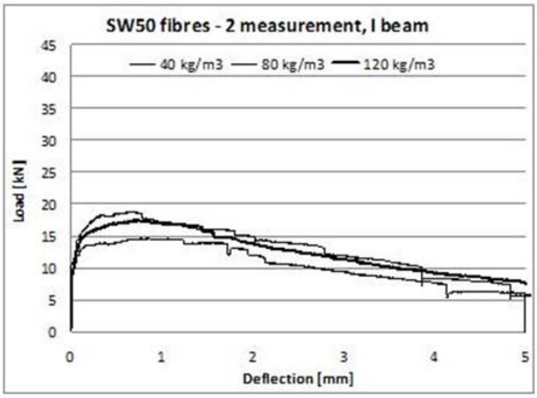


Fig. 7: Effect of steel fibres SW50 on the tensile strength in bending of beams I and II in the second measurement

The presented test results show significant differences in strength parameters of SFRSCC beams in relation to the distance to the point their formation. Increase of this distance significantly improves the strength parameters. This is definitely related to the directional orientation of the fibres taking position perpendicular to the applied force causing the bending, and to the parallel anchoring in the element subject to bending. Fibres as dispersed reinforcement but at the same time as directional reinforcement significantly improve the mechanical properties of concrete with their addition. SW50 -- longer -- fibres in a much better way "work" as a directional dispersed reinforcement as a function of distance from the molding point of the SFRSCC mix.

In the paper, there are not presented any results of the compressive strength of the SFRSCC samples, because of insignificant effect of steel fibres on this parameter, which has been confirmed in other studies, including [11] [12]. Based on previous studies [13], [14], the authors have shown how small changes were in compressive strength with the increasing volume ratio of steel fibres in the SCC.

On the basis of the presented selected cross-sections of SFRSCC, there was proved uneven distribution of steel fibres in the entire volume of the samples. No high concentrations of fibres in the concrete matrix were detected. Clearly visible is the orientation of fibres parallel to the direction of the mix flow during molding, particularly for fibres SW 50. Only few fibres are perpendicular to this direction. It should be noted that the characteristic rounding of the images of cross-sections of the concrete beam, related to the nature of computed tomography, are not the caused by the method of scanning. One can specify the phenomenon as a "pipe" movement of the mixture in the volume of the form, its sticking to the walls of the form, resulting in a particular shape of the cross-section of the flow, observed in the CT.

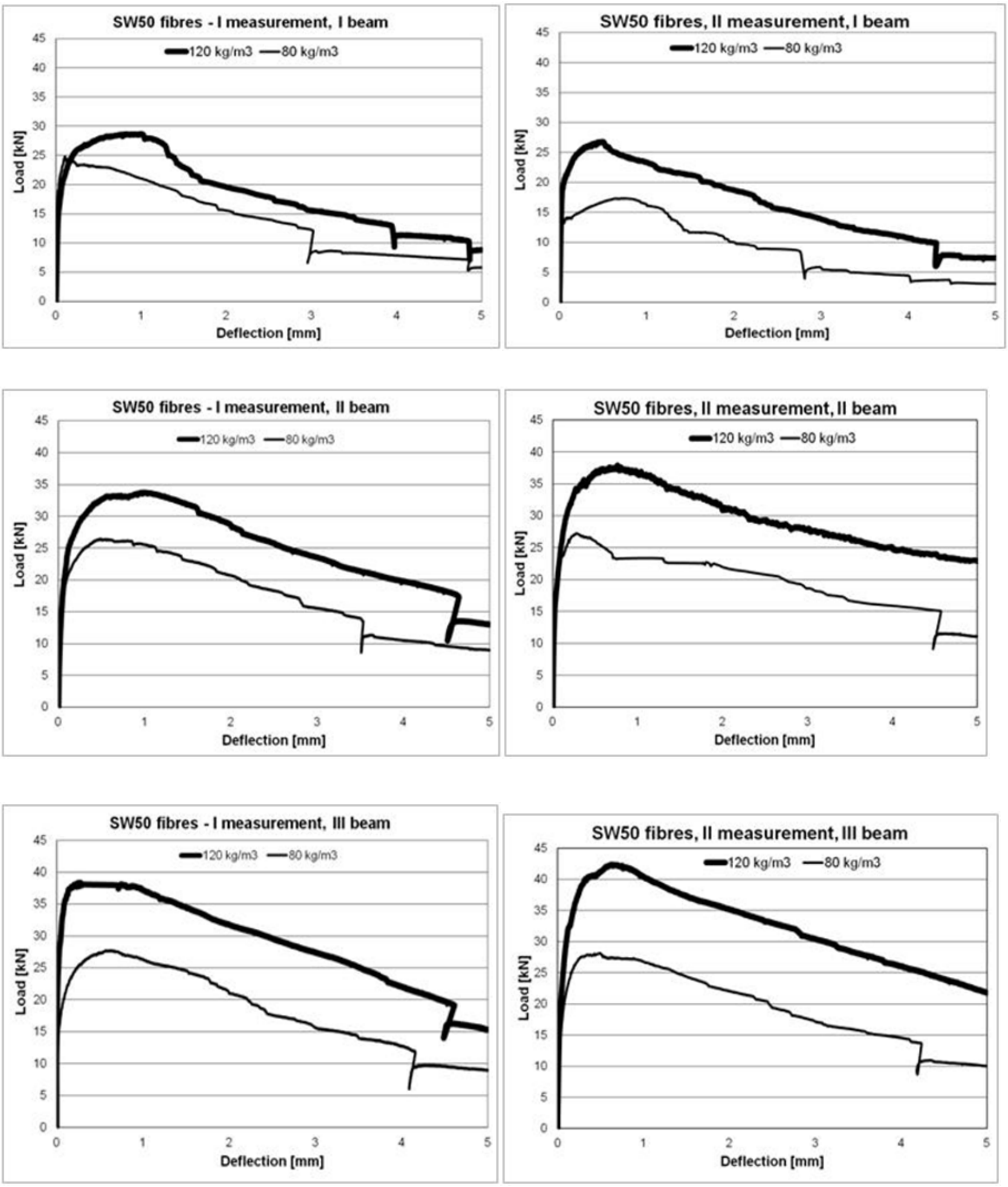


Fig. 8: Effect of steel fibres SW50 on the tensile strength in bending of I-II-III beams in the first (left figures) and second measurement (right figures).

4 CONCLUSIONS

The study confirms the technological problems with uniformity of distribution of steel fibres in the matrix of SCC. The simulation of the flow of concrete mix in the form showed the placing of fibres in direction parallel to the flow of the mix. This phenomenon intensifies in case of the longer SW50 fibres added to SCC and with the increase of their volume content. Such orientation of fibres, however, resulted in the improvement of the strength in bending of the tested SCC with the longer SW50 added. The increase in flexural strength was greater even by 80% in the case of 120 kg/m^3 SW50 fibre content in the beam type II (farther from the point of forming) in comparison with the beam I (proximal), when beams were cut from a formed beam with dimensions 120×15×15 cm^3. Similar but somewhat smaller increases were found in the beam III in comparison with beam I (cut from a beam 180×15×15 cm^3). Based on the results of the deployment of steel fibres in concrete beams with the use of computed tomography, the possibility of analyzing the position of fibres in the whole volume of the SCC was proved. Such analysis allows for testing the deployment of the steel fibres in the entire volume of the concrete, as well as in small, selected areas. It enables one also to discover trends in the arrangement of fibres in relation to the direction of forming of the concrete mix, both in proximity of the sides of the mold, and – vertically -- near the upper surface or near the bottom of the mold. Computed tomography allows for two-dimensional 2D and three-dimensional 3D images for distribution of fibres throughout the internal volume of the concrete. Results, obtained in the presented and planned studies, will form the basis for the development of methods of designing fibre reinforced self-compacting applied for various, selected structural elements. The core of the problem is to determine how in various structures the dispersed reinforcement is arranged depending on the forming of the mixture, taking into account its rheological properties, the volume and the geometrical parameters of steel fibres. The obtained test results can be used to increase the accuracy of modeling the mechanical properties of selected structural elements made from SCC with distributed reinforcement.

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